1 March 2019An active optical frequency reference using a pulsed superradiant laser

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Abstract
We will describe a next-generation active atomic frequency reference based on super-radiant pulses of laser light from the ultra-narrow, 1 mHz linewidth, optical clock transition in an ensemble of cold ^{87}Sr atoms. Light is stimulated from the millihertz linewidth transition by confining an ensemble of laser cooled atoms inside of a high finesse optical cavity. Such a light source has been proposed as a next-generation active atomic frequency reference, with the potential to enable high-precision optical frequency references to be used outside laboratory environments. We achieve a remarkable short term fractional frequency stability, 6.7 × 10^{16} at 1 s of averaging, absolute accuracy, 2 Hz (4 × 10^{15} fractional frequency), and high insensitivity to changes in the cavity length that limits the performance of todays more stable lasers. We will also discuss current work on cavity-enhanced dispersive measurements to perform high resolution spectroscopy and atom counting.

Conference Presentation

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1. INTRODUCTION

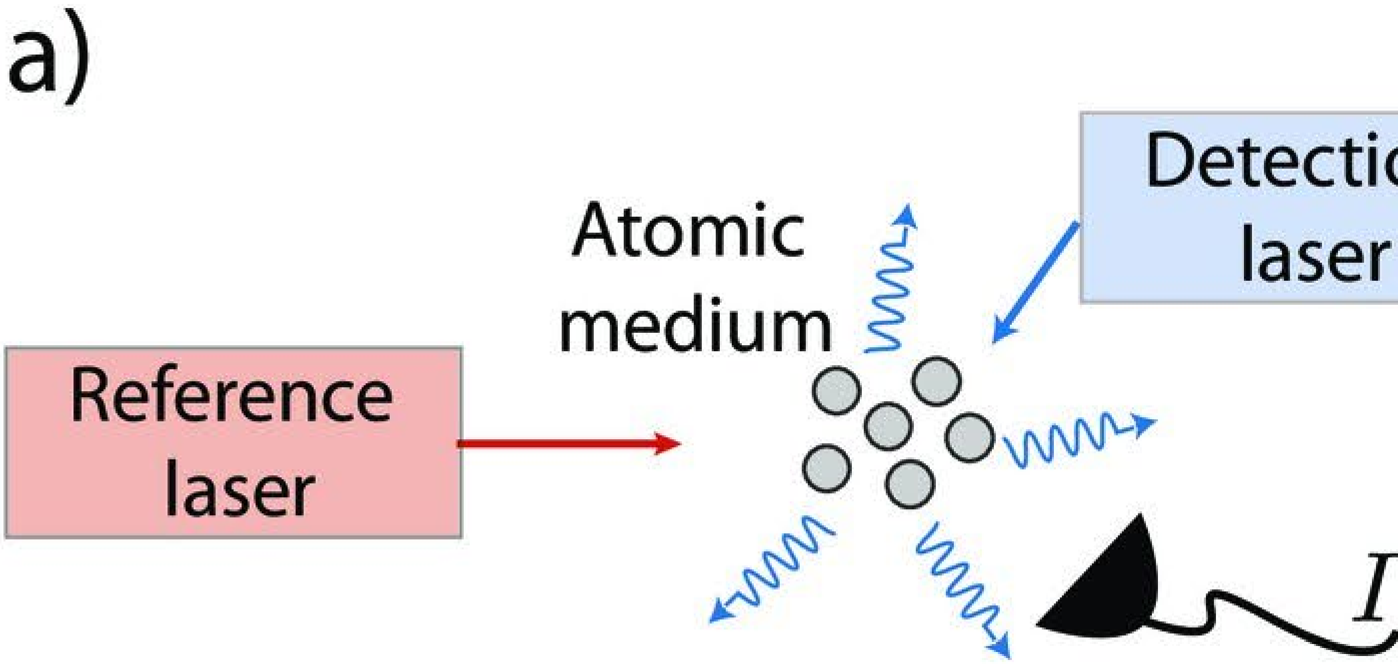
Atomic frequency standards have an increasing number of applications from technology to fundamental physics. Currently, atomic clocks based on microwave transitions define the SI second[1,2] and are fundamental for network synchronization and satellite based navigation systems such as the global positioning system (GPS).[3,4] With time, atomic clocks based on narrow optical transitions have pushed the frontier of precision frequency metrology, surpassing its microwave counterparts.[5–13] Among other applications, optical atomic clocks have been proposed to study quantum many-body physics,[14–16] as state-of-the-art geodesy instruments,[17–19] to test variation in fundamental constants,[20] to test fundamental symmetries,[21] and potentially detect, with table-top size experiments, exotic physics as passing dark matter particles.[22,23]

The timekeeping element of a clock takes the form of a stable oscillator (e.g. a balance wheel, a crystal oscillator or a laser) whose frequency is typically read. This frequency could be actively stabilized to some precise frequency reference.[24] The oscillator provides short-term stability, while the frequency reference provides long-term stability and absolute accuracy. Optical atomic clocks typically function by combining a laser as the stable oscillator and an atomic frequency reference, which is an atom or collection of atoms with a well-suited transition between internal states (the “clock transition”) to which the oscillator is stabilized.

There are two type of atomic frequency reference: active or passive.[24] In a passive reference, as sketched in Fig. 1(a), radiation from the oscillator, the laser, is applied to the atoms in a spectroscopic sequence that maps the oscillator’s frequency to internal state populations in the atoms. The populations are then measured to infer and stabilize the oscillator’s frequency.[12,25,26] In each of these experimental trials, information is obtained for one specific laser frequency, f_l, as seen in Fig. 1(a). Examples include cesium and rubidium clocks in the microwave domain,[27,28] and strontium, ytterbium, and aluminum ion clocks in the optical domain.[12]

Figure 1. Download

Passive and active optical frequency references. (a) In a passive optical frequency reference, the “clock transition” in the atomic medium is driven by radiation from a laser at frequency f_t. The laser frequency is then determined relative to the clock transition frequency through a population measurement of the two clock states, which could be used to stabilize the frequency of the laser. Each experiment provides information about the current laser frequency with respect to the atomic transition frequency. (b) In an active optical frequency reference, light is collected directly from the atomic clock transition. This light can be compared to the reference laser by forming a heterodyne beat-note. The power spectral density of the resulting signal ($\tilde{I}$) provides information about the atomic system at all offset frequencies from the laser frequency. Figure reproduced from Ref. 36.



On the other hand, in an active reference, radiation is collected directly from the clock transition, as depicted in Fig. 1(b). A typical example is the hydrogen maser,[29] which is an active frequency reference in the microwave domain. In the optical domain, an active atomic frequency reference candidate is the superradiant laser, as proposed in Ref. 30,31, and sketched in Fig. 1(b). This superradiant laser consists of an ensemble of cold atoms with a suitable ultra-narrow transition, trapped inside a highly damped optical cavity. The ensemble of atoms behave as a collective dipole, strongly coupled to the cavity mode. When the atoms are excited, they will decay into the cavity mode, in a collective process called superradiance emission.[32–34] A promise of this active frequency reference is that its spectral properties will be highly insensitive to cavity frequency noise, which is fundamentally difficult to overcome in ultra-stable lasers.[35]

The quality factor of optical transitions could be much larger than its microwave counterparts, which constitutes a huge fundamental advantage that has allowed passive optical frequency references to overtake their microwave counterparts in both precision and accuracy over the last two decades.[12,25] Here, we comment on our latest results[36] where we used our ^{87}Sr superradiant laser, operating in the ultra-narrow 1 mHz clock transition, as the first active optical frequency reference[36] to realize this advantage as proposed in references.[30,31] Until now, there have been no high-precision active atomic frequency references in the optical domain.

Furthermore, we present our progress towards cavity-enhanced dispersive measurements on the ultra-narrow clock transition. These technique allow us to measure the phase change on the light that transits our optical cavity, that depends, among other things, on the atom-light coupling strength and the atom number.[37] Our measurements could be performed without significant photon scattering, that would destroy the coherent properties of an atomic quantum state. This technique is proposed as a way to measure fundamental atomic properties in a spectroscopic way, such as the dipole element of the clock transition, as well as to allow dynamical non-destructive atom counting measurements.

2. EXPERIMENTAL SETUP

Our system, described previously in Ref. 36,38,39, consists of an ensemble of up to several 10^5 ^{87}Sr atoms confined within a high finesse optical cavity by a near-magic wavelength[40] 813 nm optical lattice that is supported by the cavity. This lattice fulfills two main roles: it tightly confines the atoms along the cavity axis, eliminating Doppler shifts, and it imparts a near equal shifts to the clock states of the lasing transition, the $^1S_0$ ground state and the $^3P_0$ excited state, as shown in Fig. 1(c). The cavity is locked at frequency f_c, close to the frequency f_a of the dipole-forbidden optical clock transition near 698 nm, which has a radiative linewidth of 1.1(3) mHz.[41] At 698 nm, the cavity's finesse is 2.5×10^4, and its linewidth is $\kappa = 2\pi \times 145$ kHz, placing the system in a highly damped, "superradiant" regime. In typical operation, the cavity detuning $\delta_c = f_c - f_a$, is nominally zero ($\delta_c \ll \kappa$), but can be varied for characterization purposes.

Atoms are initialized in one or more ground states, after which a coherent drive on the clock transition, using a laser that is coupled through the optical cavity, prepares them in a superposition of the ground and excited state. The duration of the preparation pulse sets the population inversion. After this pulse is turned off, the atoms emit collectively into the cavity.[38] We refer to this process as superradiant emission, which describes the collective radiation of an ensemble of emitters into a highly damped optical mode. After the atoms emit a superradiant pulse, a new ensemble of atoms is laser cooled and trapped and the sequence is repeated with a typical total cycle time T_c = 1.1 s.

The light emitted by the atoms into the cavity mode constitutes our superradiant laser. In order to study its spectral properties, we form a heterodyne beat-note between the light emitted from the strontium atoms and light from a state-of-the-art stable laser system that we refer to as the reference laser, as shown in Fig. 1(b). The reference laser system is described in[42,43] and is stabilized to an optical reference cavity with a thermal noise floor of 1×10^{-16} from 1 to 1000 seconds, and a linewidth of 26 mHz.

3. SUPERRADIANT LASER AS AN ACTIVE OPTICAL FREQUENCY REFERENCE

Two main aspects characterize this active frequency reference as such. One is its stability, while the other is its absolute accuracy. To quantify the stability of our superradiant source, we rely on the commonly-used metric of the fractional Allan deviation.[44] We start by populating the atoms in both stretched ground states $m_F = \pm 9/2$, and applying a π–polarized preparation pulse that will populate both excited $m_F = \pm 9/2$ states, respectively. In the prescence of a magnetic field, the frequency spectrum of the beat note is described by two peaks, one corresponding to each Zeeman-shifted excited state, as seen in Fig. 2(a) inset. In each run of the experiment, the frequency of each lasing component, $f_{\pm 9/2}$, is determined from the center of a Lorentzian fitted to each of the peaks in the power spectrum of the beat-note. For most of our measurements, the width of each peak is Fourier limited by the observation window (about 100 ms).

Figure 2. Download

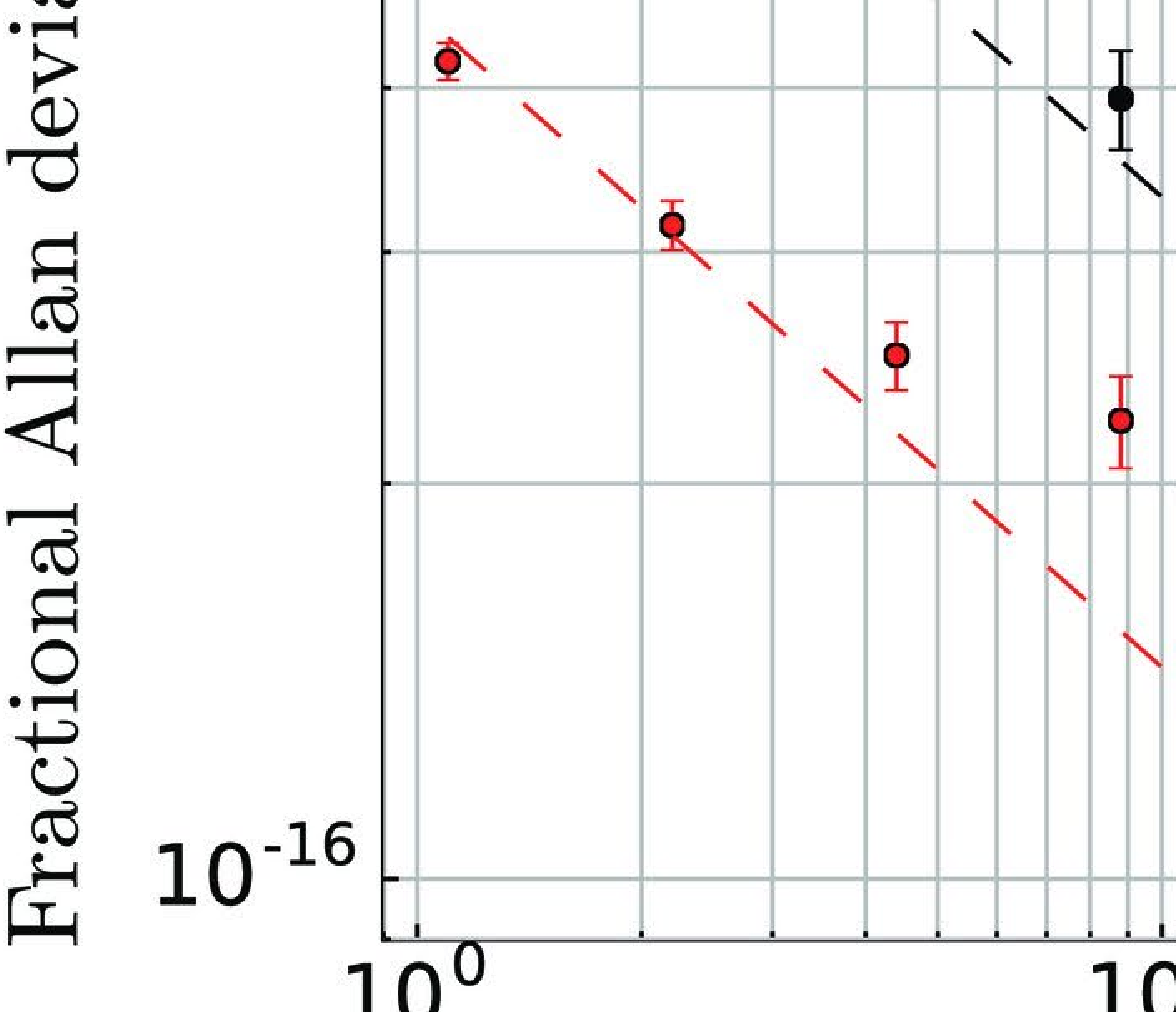
Stability and accuracy of the superradiant laser. (a) Short-term stability of superradiant light source expressed as fractional Allan deviation $\sigma(\tau)$. We populate both stretched states and compute the Allan deviation for two quantities, as shown in the inset and described in the text: the average frequency of the two lasing transitions f_m (black) and half the difference of the two lasing transition frequencies f_d (red points). We measure a short-term fractional instability of

$$\sigma(\tau) = 1.04(4) \times 10^{-15}/\sqrt{\tau/s}$$

for f_m (black dashed line), and

$$\sigma(\tau) = 4.5(2) \times 10^{-16}/\sqrt{\tau/s}$$

for f_d (red dashed line). (b) Lattice-induced frequency shifts. Measurement shows superradiant light frequency shifts, with respect to an optical atomic clock,[9] for three different trap depths (U = 1025, 760, 570 E_{rec} for green, red and blue points respectively, where E_{rec} is the lattice recoil energy), at four different lattice detunings. A global linear fit to the whole data set gives an lattice independent frequency offset (horizontal dashed line, with the uncertainty of the fit represented by the red band), and the magic wavelength (vertical dashed line, with fit uncertainty given by the green band). (c) Sensitivity of superradiant light frequency, f_m, to detuning of the cavity from resonance, δ_c, for different initial population inversions, as sketched on the side insets. An offset frequency f_0 set by the detuning of the reference laser from the strontium transition is subtracted for each data set. When tuned to minimize sensitivity to cavity detuning (red line, points) we observe a pulling coefficient $P = 2(3) \times 10^{-6}$. Changing the duration of the state preparation pulse leads to an increased absolute value of P (black, blue points). Figure reproduced from Ref. 36.



a)
Fractional Allan deviation $\sigma(\tau)$
10^{-15}
10^{-16}
10^{0}

In contrast to a passive frequency reference, we obtain information about the emitted light at all detunings with respect to the laser light. This is a fundamental advantage of this source, because it offers increased detection bandwidth and dynamic range, which can be relevant outside laboratory environments, and in mobile applications. For example, in contrast to passive frequency references, our active frequency reference can still track large excursions of the oscillator frequency and does not require the optical cavity to be precisely on resonance, as long as still enhances the atomic emission.

The Allan deviation of the frequencies of our superradiant pulses, $\sigma(\tau)$, is shown in Fig. 2(a). In this measurement, we compute the Allan deviation for two quantities: the average frequency of the two lasing transitions $f_m = (f_{9/2} + f_{-9/2})/2$ (black points), which provides an indication of the stability of our system if used as an optical frequency reference, and half the difference of the two lasing transition frequencies $f_d = (f_{9/2} - f_{-9/2})/2$ (red points), which provides a means of assessing the fundamental limits of our system. For the black points, we have measured

$$\sigma(\tau) = 1.04(4) \times 10^{-15}/\sqrt{\tau/s} \text{ fo}$$

. Our most favorable measurement of this value was

$$\sigma(\tau) = 6.7(1) \times 10^{-16}/\sqrt{\tau/s}$$

obtained for a different, shorter set of data. This corresponds to a standard deviation of 300 mHz.

Importantly, the mean frequency f_m is insensitive to magnetic field fluctuations, that would shift each peak in opposite directions. Other perturbations, such as noise on the reference laser, cavity pulling effects, and shifts associated with atomic density, would perturb the measurement of f_m. The short-term stability of f_m is also limited by photon-shot noise, as each atom emits at most one photon, and our total quantum efficiency is $\Pi = 0.06$, in contrast with most optical atomic clocks, which are rather limited by atom shot noise, as each atom can scatter multiple photons during the state projection measurement.

This can be further investigated by studying the dependence of another quantity that is insensitive to these last few perturbations. That is the frequency difference f_d, that is unchanged under perturbations that affects both lasing transitions in the same manner. For the data set corresponding to the black points of Fig. 2(a), f_d exhibits a short-term stability of

$$\sigma(\tau) = 4.5(2) \times 10^{-16}/\sqrt{\tau/s}$$

. This quantity constitutes a synchronous comparison of the atoms populating each of the two stretched states, and is limited mostly by photon shot noise associated with the superradiant pulse.

The stable reference laser noise accounts for most of the difference between the measured Allan deviations for f_m and f_d at short times ($\tau \lesssim 10$ s), through down-conversion of high-frequency noise to lower frequencies (Dick effect[45]), due to the finite sampling fraction per experimental cycle. For longer averaging windows (large τ), the measured Allan deviations flatten out near the reference laser noise floor (around $\sigma(\tau) = 1 \times 10^{-16}$ from 1 to 1000 seconds[42,43]), as seen in the fluctuations in average frequencies f_m (black points).

In order to assess the absolute accuracy of the superradiant light source, we perform a comparison with the optical lattice clock described in Ref. 9. For this comparison, we account for known shifts to the frequencies of both the lattice clock and superradiant system at the Hz level, see Ref. 36 for further details.

The largest of such shifts is due to the differential AC Stark shift from the optical lattice. By measuring the frequency of our superradiant pulse laser with respect to the optical atomic clock,[9] at different lattice depths and detunings, as shown in Fig. 2(b), we can obtain measure the systematic frequency shift between the two systems. After accounting for other known shifts,[36] the measured frequency difference between our superradiant light and the value measured by the optical lattice clock is 1 ± 2 Hz (fractionally $2(4) \times 10^{-15}$).

The superradiant laser works on a regime where the atomic coherence tracks the phase of the reference oscillator, while the cavity field has a short lifetime. Therefore, the frequency of the superradiant light is highly insensitive to technical and fundamental thermal fluctuations in cavity length that limit todays most stable lasers. As described in Ref. 36,46, different collective effects create frequency shifts ($\delta f_{SR} = f_m - f_0$, where f_0 is an offset frequency) on the superradiant emitted light that depend on the cavity detuning from the atomic transition (δ_c).

To characterize those effects, we measured the shifts on the emitted light as function of the cavity detuning. We quantify this shift by the pulling coefficient P, defined as $P = \delta f_{SR}/\delta_c$. Because P depends linearly on the population inversion,[46] it will change sign if most of the atoms are initialized in the ground or excited states. Furthermore, as the inversion changes during the superradiant pulse, the measured shift is effectively averaged over the duration of the pulse, as shown in Fig. 2(c) for different initial conditions. When the initial conditions are tuned to minimize the pulling coefficient, we measure a value as low as $P = 2(3) \times 10^{-6}$. It is worth mentioning that this is a characteristic of the pulsed system. A continuous superradiant laser will have a positive population inversion, and therefore these effects will not average down. However, we still expect to achieve $P \ll 1$.

4. CAVITY-ENHANCED DISPERSIVE MEASUREMENTS

Many cavity QED experiments work in the so called strong-coupling regime, where the frequency of interaction between a single atom and the cavity mode, g, is significantly bigger than any other dissipation rates, such as κ and γ. In cases where there are N atoms coupled to the cavity mode, this condition can be written as $NC \gg 1$, where $C = (2g)^2/\kappa\gamma$ is the cooperativity.[47,48]

A clear manifestation of this regime has been the observation of vacuum Rabi splitting in multiple setups, as in Ref. 49–53 for example, for cases where $\sqrt{N}g \gg \kappa$. In our experiment, this condition is fulfilled on the narrow 7.5 kHz linewidth transition, between the $^1S_0$ ground state and $^3P_1$ excited state, at $\lambda_N = 689$ nm.[54] However, for the ultra-narrow 1 mHz clock transition at $\lambda_C = 698$ nm, this condition is not satisfied. Consequently, when the cavity is on resonance with the narrow transition at λ_N, two distinct peaks can be observed. On the other hand, when the cavity is on resonance with the ultra-narrow transition at λ_C, these peaks will not be resolved.[55]

In the latter, the atoms still have an effect over the light that propagates through the cavity. That effect manifests in two ways. Firstly, the atoms can absorb, and eventually emit, some of probe photos. Secondly, the atoms phase shift the intra-cavity electric field, which we call dispersive phase shift. When the probe is sufficiently detuned from the atomic resonance, the dispersive effects overcome the dissipative ones. Intuitively, the atomic medium modifies the optical path length that the light transits while reflecting between the cavity mirrors. The phase shift for this probe is

$$\Delta\phi_C = -(N_g - N_e)\gamma C/(2\delta_p)$$

, where δ_p is the detuning between the driving field and the atomic transition, and N_e and N_g are the number of atoms in the ground and excited clock states, respectively. The apparent advantage of measuring the phase shift of a far detuned probe ($\delta_p >> \gamma$) is that one can decreases the excitation fraction induced by the measuring process itself, which usually scales with

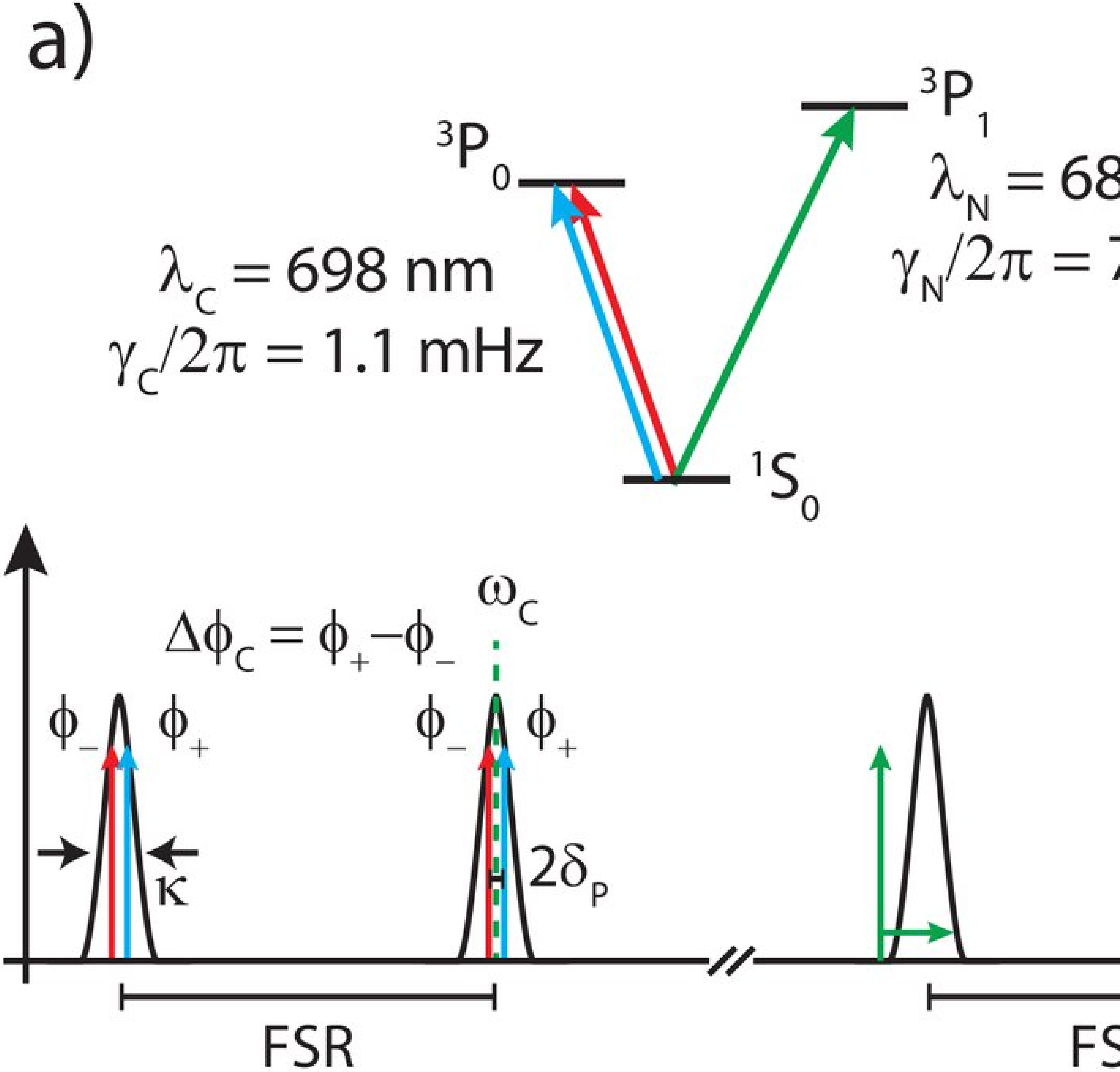
$$N_e/N \propto 1/\delta_p^2$$

. This technique has been proposed in the past, for instance, to perform non-demolition measurements of atomic populations,[56] sub-Poissonian atom counting[57] or monitoring atomic coherences.[58]

The light that transits the cavity not only sees the atomic phase shift, but also the shift provided by the cavity itself. In order to isolate the atomic contribution, and remove noise sources, we weakly probe the cavity with two probes detuned $\pm\delta_p$ from the atomic transition, with the cavity resonance ($\delta_c = 0$), while probing an adjacent[2] longitudinal mode of the cavity, about 3.8 GHz away, as sketched in Fig. 3(a). This allow us to remove any cavity-only phase shift contribution, that will be identical on both pairs of probes. This configuration provides enhanced insensitivity with respect to cavity center frequency fluctuations, cavity and atomic frequency alignment, and small fluctuations in the atomic frequency. While probing one of the cavity modes, after performing an heterodyne measurement, the demodulated signal looks like the one shown in Fig. 3(b)(i).

Figure 3. Download

Cavity-enhanced dispersive measurements. (a) Atomic structure and relevant properties for ultra-narrow 1 mHz and the narrow 7.5 kHz transitions. Different probes for measuring atomic phase shifts at the ultra-narrow transition, $\Delta\phi_C$, and cavity frequency shifts, $\Delta\omega_N$, on the narrow transition. This schemes suppresses cavity frequency noise, as well as atom number fluctuations. (b) Example of demodulated signals used to extract phases and cavity frequency center. (i) Beating between two tones at $\pm\delta_P = \pm 1$ kHz from the clock transition. (ii) Probe sweeping across the cavity resonance on the narrow transition. (c) Measured $\Delta\phi_C$ and $\Delta\omega_N$ for different atom numbers. In this measurement, the excitation fraction in the clock transition is not negligible.



On the other narrow transition in neutral [87]Sr at λ_N, the collective coupling, i.e. Ng_N^2, where g_N is the light-atom coupling associated with this transition as before, is big enough to overcome the dissipative behaviour. If there is a cavity mode detuned δ_N^C from the atomic transition at λ_N, the cavity resonance frequency will be shifted by

$$\Delta\omega_N = N g_N^2/\delta_N^C$$

.[59] A measurement of the cavity resonance frequency can be done by sweeping the frequency of a weak probe across the cavity resonance. By probing simultaneously a different and further detuned cavity longitudinal mode, as shown in Fig. 3(a), the measurement can be made insensitive to cavity frequency noise.[60] A typical measurement after demodulation looks like the one in Fig. 3(b)(ii).

As our cavity can support high finesse modes at both wavelengths, we can perform consecutive measurements on the two transitions. If the probe power is low enough, such that most of the atoms remain in the ground state, a phase shift measurement on the clock transition using the configuration described before, $\Delta\phi_C$, can be complemented with a simultaneous cavity frequency shift, $\Delta\omega_N$, on the narrow transition at λ_N, to have further atom number insensitivity. Moreover, the two measurements have the same degree of inhomogeneity in the coupling strength g_N and g_C, due to the fact that the probe wavelengths are incommensurate with the lattice wavelength, which simplifies greatly the analysis. As an example, we show in Fig. 3(c) a simultaneous measurement of $\Delta\phi_C$ and $\Delta\omega_N$, where each point represents a different atom number loaded into the lattice.

Dispersive measurements are preferred in order to perform non-demolition measurements, as required, for instance, for several spin-squeezing experiments.[60–62] So far, on alkaline-earth atoms, these measurements have limited to atom counting in the 7.5 kHz narrow transition.[54] On the clock transition, these measurements have the potential to be used as a non-destructive atom-counting tool, allowing, for example, the possibility to evaluate dynamical behaviour on driven systems.[63]

5. OUTLOOK

In this work we have demonstrated the first optical high-precision active atomic frequency reference to date, with a short-term stability that already surpasses that of existing active atomic frequency references (masers), and intrinsic insensitivity to various environmental perturbation sources, as drifts in the optical cavity frequency and to fluctuating magnetic fields. In terms of the absolute accuracy of this active frequency reference, we have characterized its systematic frequency shifts to the Hz level.

In the near future, it will be advantageous to extend the pulsed mode of operation demonstrated here to steady-state operation. Doing so would mean to overcome the limitations photon shot noise present for its short-time stability. In order to do so, a system with constant inversion must be prepared, for instance, by either incoherently pumping atoms from the ground to the excited state, or bringing new fresh atoms in the excited state at a steady rate. Work is under development to create such a frequency reference source.

Furthermore, we have commented on ongoing efforts to perform dispersive measurements on the clock transition. These scheme shows great insensitivity to cavity frequency noise and atom number fluctuations, and allows to measure real time population dynamics on the clock states as well as performing precise spectroscopy on the clock transition. Performing such measurements on the clock transition have fundamental implication on future optical atomic clocks.

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